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OVERWATER OPTICAL SCINTILLATION MEASUREMENTS DURING MAGAT-1980.(U)  
AUG 80 E C CRITTENDEN, E A MILNE, A W COOPER

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## Monterey, California



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### TECHNICAL REPORT

Overwater Optical Scintillation Measurements  
during MAGAT-1980

E. C. Crittenden, Jr., E. A. Milne  
A. W. Cooper, G. W. Rodeback  
and S. H. Kalmbach

Optical Propagation Group  
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August, 1980

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20. The overwater path length was 13.3 km. The light source was a 10.6 micrometer CO<sub>2</sub> laser. This combination of range and wavelength was adequate to avoid saturation effects.

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Abstract

Overwater measurements have been made of the turbulence structure constant for index of refraction,  $C_n^2$ , by means of scintillation, for comparison with predictions of  $C_n^2$  based on meteorological measurements carried out at the same time, during the "Monterey Aerosol Generation and Transport" (MAGAT-80) experiment, 27 April to 9 May, 1980. Scintillation was chosen as the optical measurement because it gives heaviest weight to points on the optical path near the center of the path, minimizing the shoreline influence. The overwater path length was 13.3 km. The light source was a 10.6 micrometer  $\text{CO}_2$  laser. This combination of range and wavelength was adequate to avoid saturation effects.

## FIGURES

Figure 1. Optical paths across Monterey Bay.

Figure 2. Relative weighting of  $C_n^2$  as a function of position along the path, for MTF and for scintillation. The telescope end of the path is at the right.

Figure 3. Probability density curve for determination of  $C_n$ .

## TABLES

Table I. Sample data print-out.

## Introduction

Models for the prediction of the turbulence structure constant for index of refraction,  $C_n^2$ , have often suffered from a lack of directly measured values of  $C_n^2$  for comparison with predictions. To resolve this uncertainty during a continuous series of experiments between 27 April and 9 May, 1980, measurements were made of  $C_n^2$ , by optical means, along a 13.3 km. overwater optical path between Marina and Pt. Pinos on Monterey Bay. In addition to the optical measurements, the overall experimental program included meteorological measurements made aboard the R/V Acania and aboard an aircraft operating in the vicinity. Measurements were made in the vicinity of the optical path as well as seaward of the path and overhead in the same regions. The meteorological results and modeling for prediction of  $C_n^2$  are reported in another NPS report<sup>(1)</sup>. The optical measurements were made regularly on a six-hour interval basis throughout the experimental period. Measurements were also made every half hour during a number of periods of "high level" activity of all the participating teams.

## Experimental Program

The geography of Monterey Bay is well suited for  $C_n^2$  measurements. Optical paths across the bay are available as shown in Figure 1. Since the modeling predictions are presumably most applicable far from shore, it is desirable to use techniques that emphasize  $C_n^2$  near the center of the optical path. The relative weighting of points on the optical path is shown in Figure 2, for use of scintillation, and for use of resolution (MTF) to measure  $C_n^2$ . Scintillation is the preferred method of measurement, as it emphasizes the center of the optical path.

(1) Naval Postgraduate School Report NPS61-80-016, "Verification of the Bulk Model for Calculations of the Overwater Index of Refraction Structure Constant",  $C_n^2$ . Davidson, Schacher, Fairall, Spiel, Crittenden, and Milne, July, 1980.



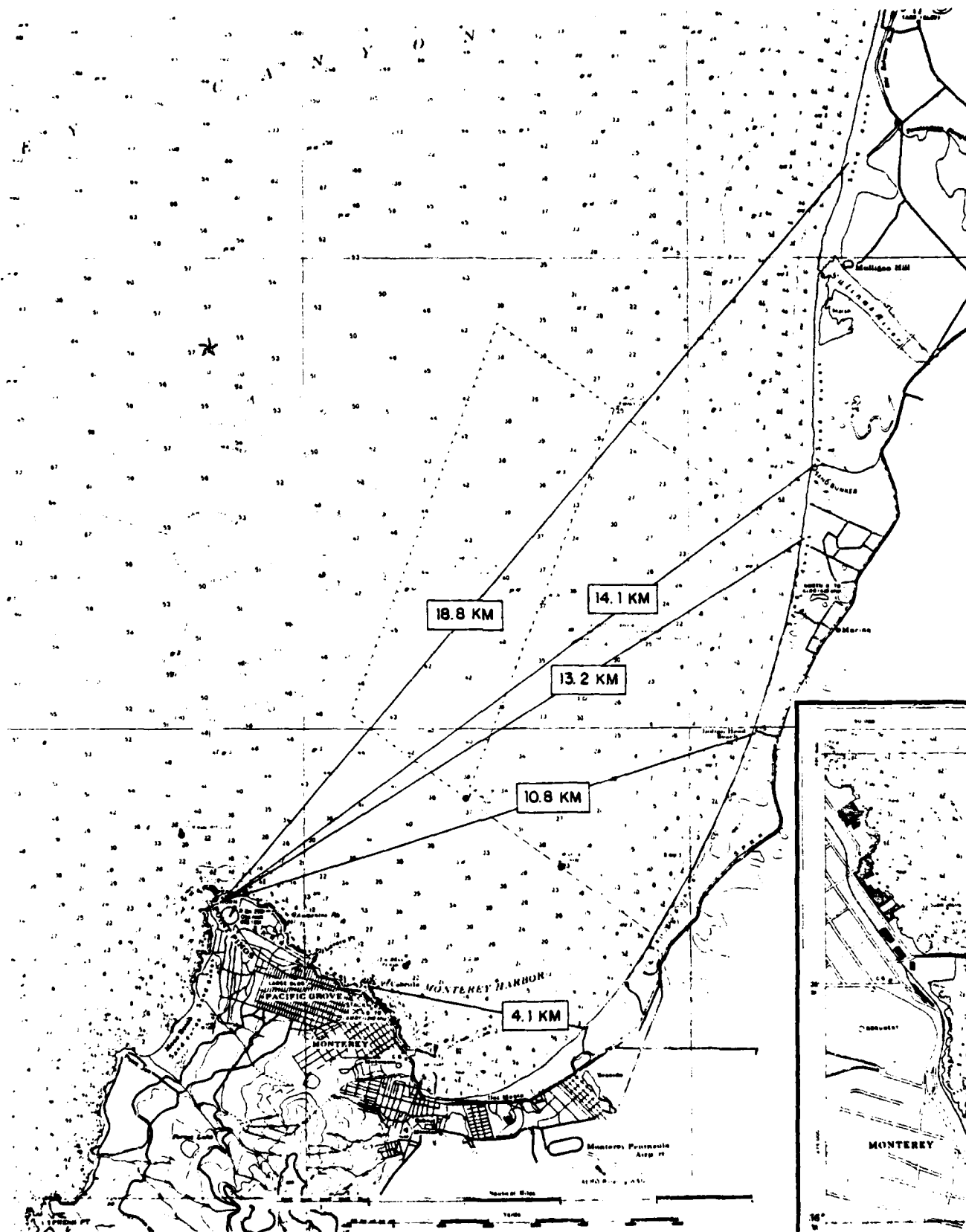


Fig. 1. Optical Ranges Across Monterey Bay.

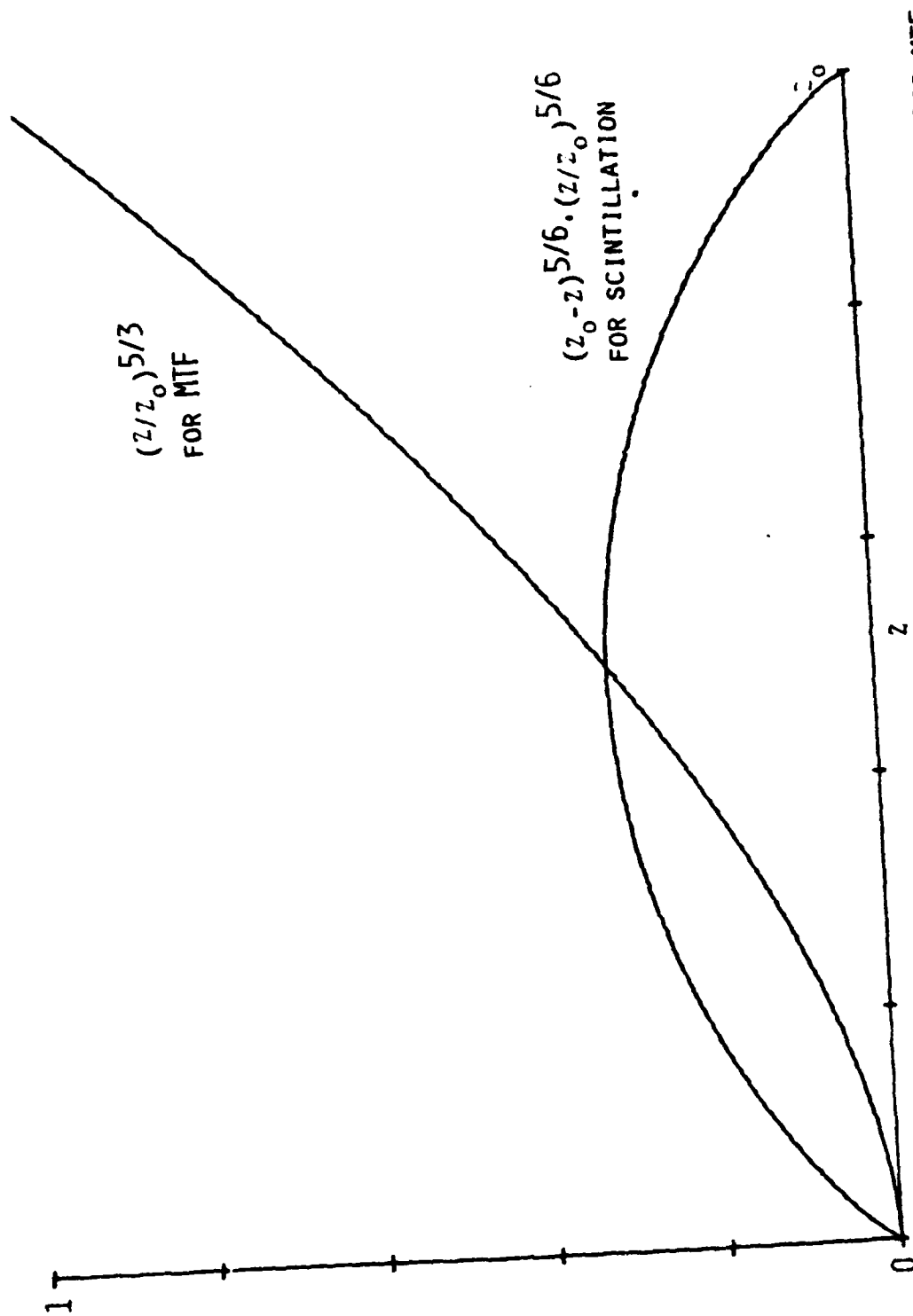


FIG. 2. RELATIVE WEIGHTING OF  $C_N^2$  AS A FUNCTION OF POSITION ALONG THE PATH, FOR MTF AND FOR SCINTILLATION. THE TELESCOPE END OF THE PATH IS AT THE RIGHT.

Measurement of  $C_n^2$  by means of scintillation involves measuring the probability density for occurrence of a given logarithm of the intensity, for spherical waves, observed through a small aperture. Curves such as that shown in Figure 3 are obtained by taking the logarithm of the received intensity electronically, and digitizing the result at a rate of approximately two kilohertz. Sigma, the root-mean-square deviation from the mean, for this distribution curve, is obtained by fitting the Gaussian distribution to the curve, as shown in Figure 3, and calculating the corresponding value of sigma. This method of measurement avoids errors due to loss of points at very high or very low intensity. The value of  $C_n$  is then obtained by use of the expression:

$$C_n = 1.42 \sigma_{\ln I} k^{-7/12} z^{-11/12}$$

where:  $\sigma_{\ln I}$  = sigma for the probability distribution curve for logarithm of intensity,  $k = 2\pi/\lambda$ ,  $z_0$  = optical path length. This expression has been well established experimentally.(2).

The phenomenon of "saturation" poses some problems in the measurement of  $C_n^2$  by means of scintillation. On progressive increase of turbulence level, the value of sigma increases, proportional to  $C_n$ , until a value of sigma of about 0.5 is reached. Beyond this value, sigma increases more slowly with increasing turbulence level, finally reaching a maximum at a value of unity. For still higher  $C_n$ , sigma can decrease below unity. It is important to realize that sigma saturates, not  $C_n$ . Inverting the previous equation:

$$\sigma_{\ln I} = 0.70 C_n k^{7/12} z^{11/12}$$

(2) Naval Postgraduate School Report, NPS61-78-003, "Optical Resolution in the Turbulent Marine Boundary Layer", Crittenden, Cooper, Milne, Rodeback, Armstead, Kalmbach, Land, and Katz, February, 1978.

Date May. 5, 1980      time 1227  
 wavelength = 10.6 micrometers  
 Range = 13160 meters  
 Sigma = 2.18E-01  
 Cn = 2.22E-08    Cn\*2 = 4.94E-16

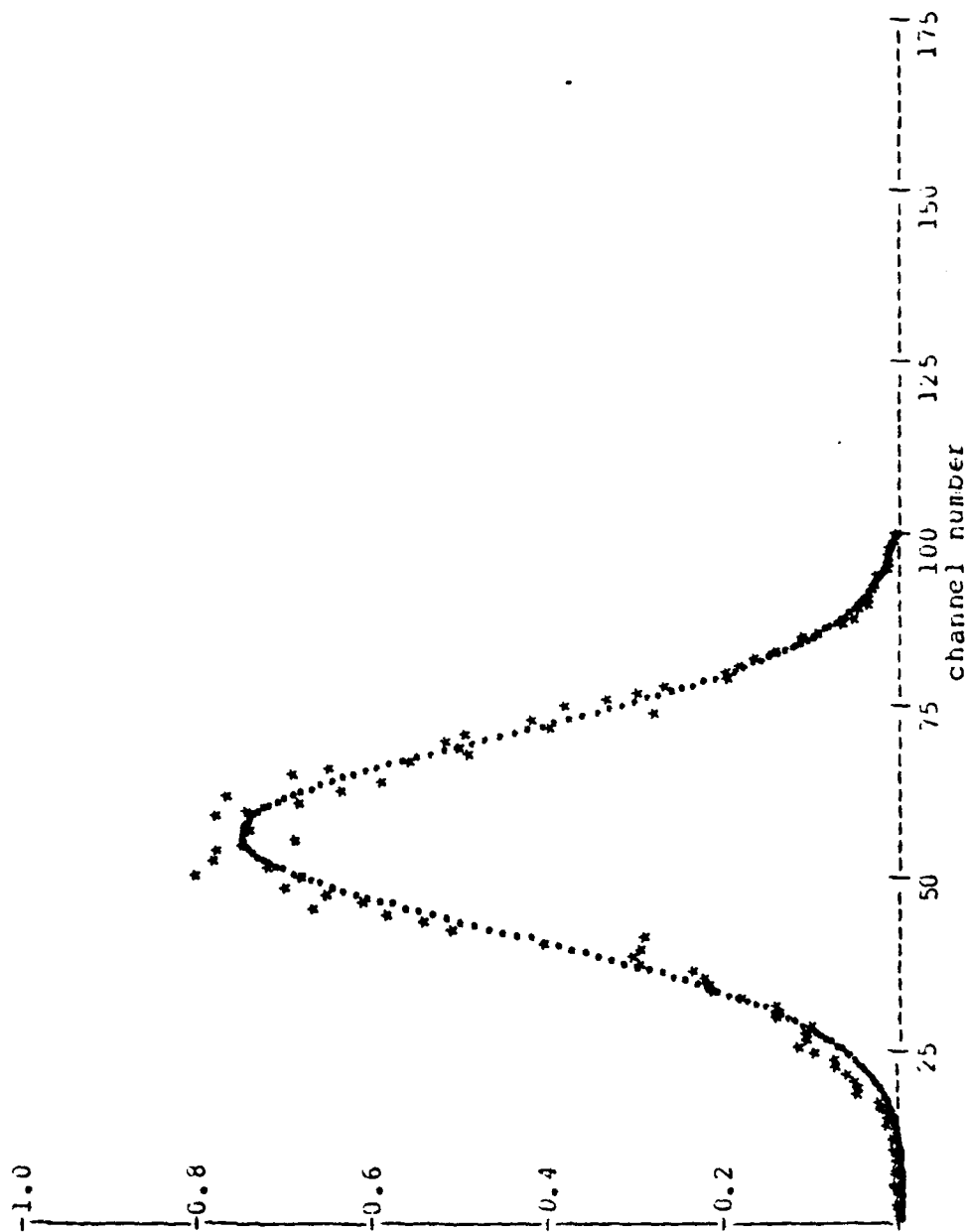


FIG. 3. PROBABILITY DENSITY CURVE FOR DETERMINATION OF  $C_N$ .

It can be seen that  $\sigma$  is reduced, for a given turbulence level, by reducing both  $k$  and  $z$ . Reducing  $k$  means using the maximum possible wavelength. In practice this is accomplished by using a  $\text{CO}_2$  laser with a wavelength of 10.6 micrometers. Reducing the range length,  $z$ , involves the problem that a short path length often leads to shoreline influence on  $C_n$ . The path chosen for this experiment has a rather long range length, 13.3 km, but it crosses Monterey Bay where there is relatively little shoreline influence. The values of  $\sigma$  encountered during the experiment approached the region of saturation in a few cases, but serious saturation apparently did not occur during the experiment.

The source laser was a 3 watt Spectra-Physics model 941 electrical discharge  $\text{CO}_2$  laser, operating at 10.6 micrometers. A back-up laser was also provided, and proved to be needed during the experiments. The back-up laser itself, in turn, had to be replaced before the end of the experiment. The lasers are water cooled, with a closed circuit de-ionized water system, cooled by heat exchange to an ice bath. Once aligned, the lasers retained alignment on the receiver across the bay.

The transmitted laser beam profile was shaped by means of a one-inch focal length germanium lens, converging the radiation to a cross-over, which in turn was located near the focus of a 3-inch diameter off-axis paraboloid front surfaced mirror. Adjustment of the angle and position relative to the focus was provided by means of microinch micrometer screws. The beam spot at the receiver had a width of about 50 meters.

The transmitted beam was chopped at a frequency of 1.0 kilohertz by means of a chopping wheel located at the focus of the germanium lens. A reference signal was obtained from the chopping wheel by means of a GaAs LED transmitting through the chopping wheel to a photocell. This reference chopped signal was amplified and used to modulate a 256.3 megahertz telemeter signal. The pulsed telemeter signal was

transmitted by means of a directive antenna array to the other end of the optical range, where it was received on a similar antenna, amplified, and used to trigger the phase sensitive detection system and the digitizer in the receiving system.

The receiving optical system was an 18-inch diameter Cassegrain telescope with a focal length of 8 meters. The large aperture was useful in initial alignment, but was stopped down at first to a 5-inch diameter circular aperture for scintillation measurement. During the first day of operation, tests were made to determine if aperture averaging were occurring. This was found to occur with the 5-inch aperture, but it was negligible for apertures of one-inch and less in diameter. Subsequent measurements were always made with the one-inch aperture, and additional measurements were also made with the 5-inch aperture to provide data with which to evaluate the small number of earlier data points taken with the 5 inch aperture.

The detector was a HgCdTe photoconductive detector, cooled to 77 K by liquid nitrogen. The signal from the detector was amplified in a Princeton Applied Research model 113 low-noise amplifier. The amplified signal was demodulated in a circuit arranged to sample the amplitude at the center of the received rectangular optical pulse, and at the center of the off-interval. The difference of these two signals was then used to construct a slowly varying signal representing the true intensity variation. This signal was then sent through a HP7562A logarithmic converter and then to the NIC-80 on-line computer. The NIC-80 digitized the signal once for every optical pulse. The sampling was timed to occur shortly after the background was sampled and subtracted from the light signal. The triggered detection amounts to a phase sensitive detection technique and provides a large increase in the signal-to-noise ratio relative to direct detection methods.

The digitized log-intensity signal was tallied in the computer to yield a probability density curve from which the best-fit Gaussian distribution was determined. The log-intensity probability density curve data for each run was stored on magnetic tape and later plotted out for each  $C_n^2$  value. The value of  $C_n^2$ , using the best-fit sigma in the equation quoted earlier, was printed out on the HP-9871 line printer. The length of each data sampling run was usually 40 seconds, or 40,000 samples. The  $C_n^2$  values are tabulated in Appendix A (separate volume).

An automatic weather recording station was also operated at the Pt. Pinos site, with print-out every half hour, for wind velocity, temperature, and relative humidity. The sensors were on a pole about 15 ft. above the ground and about 20 ft. from the foghorn building. The surroundings obviously modified the readings, so they should be used with caution.

#### Experimental Results

All results were reduced immediately by the on-line computer and printed out on the HP-9871 line printer. Copies of the results were communicated to NEPRF on a daily basis in the course of the experiments. A sample print-out appears in Table I. For the  $C_n^2$  results, the date, time, value of  $C_n$ ,  $C_n^2$  and the value of sigma of the probability density curve are printed.

In most cases scintillation was measured with two different aperture sizes, to aid in evaluating any aperture averaging. The print-out shows the aperture size as "large hole" - a 5 inch diameter aperture, or "small hole" - a one-inch diameter aperture.

May. 6, 1980 513	Wavelength = 1.0600 micrometers	Transmission = 3.60E 00%	Extinction = 2.51E-04/meters
May. 6, 1980 514	Wavelength = 1.0600 micrometers	Transmission = 4.01E 00%	Extinction = 2.44E-04/meters
May. 6, 1980 515	Wavelength = 1.0300 micrometers	Transmission = 4.39E 00%	Extinction = 2.37E-04/meters
May. 6, 1980 515	Wavelength = 1.0300 micrometers	Transmission = 4.49E 00%	Extinction = 2.36E-04/meters
May. 6, 1980 516	Wavelength = 0.8400 micrometers	Transmission = 3.57E 00%	Extinction = 2.53E-04/meters
May. 6, 1980 517	Wavelength = 0.8400 micrometers	Transmission = 4.17E 00%	Extinction = 2.41E-04/meters
May. 6, 1980 518	Wavelength = 0.6328 micrometers	Transmission = 3.36E 00%	Extinction = 2.58E-04/meters
May. 6, 1980 518	Wavelength = 0.6328 micrometers	Transmission = 3.20E 00%	Extinction = 2.62E-04/meters
May. 6, 1980 525	Temperature = 11C R Humidity = 91%	Wind speed = 3 meters/second	
Small aperture.			
May. 6, 1980 525	Cn squared = 6.43E-16	Cn = 2.55E-08	Sigma = 0.24946
Large aperture.			
May. 6, 1980 527	Cn squared = 6.13E-16	Cn = 2.48E-08	Sigma = 0.24262
Small aperture.			
May. 6, 1980 529	Cn squared = 1.19E-15	Cn = 3.45E-08	Sigma = 0.33763
May. 6, 1980 532	Temperature = 11C R Humidity = 91%	Wind speed = 3 meters/second	
May. 6, 1980 535	Wavelength = 1.0600 micrometers	Transmission = 7.01E 00%	Extinction = 2.02E-04/meters
May. 6, 1980 536	Wavelength = 1.0600 micrometers	Transmission = 7.11E 00%	Extinction = 2.01E-04/meters
May. 6, 1980 537	Wavelength = 1.0300 micrometers	Transmission = 7.00E 00%	Extinction = 2.04E-04/meters
May. 6, 1980 537	Wavelength = 1.0300 micrometers	Transmission = 6.83E 00%	Extinction = 2.16E-04/meters
May. 6, 1980 538	Wavelength = 0.8400 micrometers	Transmission = 5.82E 00%	Extinction = 2.13E-04/meters
May. 6, 1980 539	Wavelength = 0.8400 micrometers	Transmission = 5.59E 00%	Extinction = 2.31E-04/meters
May. 6, 1980 539	Wavelength = 0.6328 micrometers	Transmission = 4.77E 00%	Extinction = 2.31E-04/meters
May. 6, 1980 540	Wavelength = 0.6328 micrometers	Transmission = 4.95E 00%	Extinction = 2.29E-04/meters
May. 6, 1980 541	Temperature = 11C R Humidity = 91%	Wind speed = 3 meters/second	
Small aperture.			
May. 6, 1980 547	Cn squared = 5.36E-16	Cn = 2.32E-08	Sigma = 0.22692
Large aperture			
May. 6, 1980 549	Cn squared = 2.70E-16	Cn = 1.64E-08	Sigma = 0.16102
Small aperture.			
May. 6, 1980 551	Cn squared = 5.44E-16	Cn = 2.33E-08	Sigma = 0.22665
May. 6, 1980 554	Temperature = 11C R Humidity = 92%	Wind speed = 4 meters/second	
May. 6, 1980 559	Wavelength = 1.0600 micrometers	Transmission = 6.99E 00%	Extinction = 2.02E-04/meters
May. 6, 1980 559	Wavelength = 1.0300 micrometers	Transmission = 7.58E 00%	Extinction = 1.96E-04/meters
May. 6, 1980 559	Wavelength = 1.0300 micrometers	Transmission = 8.51E 00%	Extinction = 1.87E-04/meters
May. 6, 1980 600	Wavelength = 1.0300 micrometers	Transmission = 8.74E 00%	Extinction = 1.85E-04/meters
May. 6, 1980 600	Wavelength = 0.8400 micrometers	Transmission = 6.95E 00%	Extinction = 2.03E-04/meters
May. 6, 1980 601	Wavelength = 0.8400 micrometers	Transmission = 7.70E 00%	Extinction = 1.95E-04/meters
May. 6, 1980 602	Wavelength = 0.6328 micrometers	Transmission = 5.86E 00%	Extinction = 2.16E-04/meters
May. 6, 1980 603	Wavelength = 0.6328 micrometers	Transmission = 5.21E 00%	Extinction = 2.25E-04/meters
Small aperture.			
May. 6, 1980 604	Cn squared = 7.31E-16	Cn = 2.80E-08	Sigma = 0.27393

TABLE I. SAMPLE DATA PRINT-OUT.



Additional measurements of atmospheric transmission at four different wavelengths are also printed out. This data is part of a different experiment being conducted at the same time. The two sets of data have not been separated by transcribing, because of the danger of introducing errors.

For each  $C_n^2$  value, the probability density curve has been printed out, in order to determine if the distribution is reasonable. Such a curve appears in Figure 3, as previously discussed. The plots from the approximately 260 scintillation runs have not been included in this report because of the bulk of paper involved in reprinting them. They are available on request. The probability density data is also stored on tape and is available at any time, if desired.

A complete set of the computer print-outs for the experiment is tabulated in Appendix A of this report. This appendix is bound separately in an additional volume, and submitted in only one copy, because of the large number of pages (85 pages) and the large page size.

The meteorological data: Temperature, Relative humidity, and Wind speed are printed with the other data in Appendix A.

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